

GRB 980425 in the Off-Axis Jet Model of the Standard GRBs

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Abstract. Using a simple off-axis jet model of GRBs, we can reproduce the observed unusual properties of the prompt emission of GRB 980425, such as the extremely low isotropic equivalent γ -ray energy, the low peak energy, the high fluence ratio, and the long spectral lag when the jet with the standard energy of $\sim 10^{51}$ ergs and the opening half-angle of $10^\circ \leq \Delta\theta \leq 30^\circ$ is seen from the off-axis viewing angle $\theta_v \sim \Delta\theta + 10\gamma^{-1}$, where γ is a Lorentz factor of the jet. For our adopted fiducial parameters, if the jet that caused GRB 980425 is viewed from the on-axis direction, the intrinsic peak energy $E_p(1+z)$ is $\sim 2.0\text{--}4.0$ MeV, which corresponds to those of GRB 990123 and GRB 021004. Our model might be able to explain the other unusual properties of this event. We also discuss the connection of GRB 980425 in our model with the X-ray flash, and the origin of a class of GRBs with small E_γ such as GRB 030329.

INTRODUCTION

There are some GRBs that were thought to be associated with SNe [4, 17]. GRB 980425 / SN 1998bw, located at $z = 0.0085$ (36 Mpc), was the first event of such class [7, 11, 15, 16]. It is important to investigate whether GRB 980425 is similar to more or less typical long duration GRBs. However, GRB 980425 showed unusual observational properties. The isotropic equivalent γ -ray energy is $E_{iso} \sim 6 \times 10^{47}$ ergs and the geometrically corrected energy is $E_\gamma = (\Delta\theta)^2 E_{iso} / 2 \sim 3 \times 10^{46}$ ergs $(\Delta\theta / 0.3)^2$, where $\Delta\theta$ is the unknown jet opening half-angle. These energies are much smaller than the typical values of GRBs. The other properties of GRB 980425 are also unusual; the large low-energy flux [6], the low variability [5], the long spectral lag [14], and the slowly decaying X-ray afterglow [15, 16].

Previous works suggest that the above peculiar observed properties may be explained if the standard jet is seen from the off-axis viewing angle (e.g. [9, 13]). Following this scenario, the relativistic beaming effect reduces E_{iso} and hence E_γ . In this paper, in order to explain all of the observed properties of GRB 980425, we reconsider the prompt emission of this event using our simple jet model [21, 22, 23, 24].

SPECTRAL ANALYSIS OF GRB 980425 USING BATSE DATA

We argue the time-averaged observed spectral properties of GRB 980425. Using the BATSE data of GRB 980425, we analyze the spectrum within the time of FWHM of the peak flux in the light curve of BATSE channel 2. We fit the observed spectrum

with the Band function. The best-fit values are $\alpha = -1.0 \pm 0.3$, $\beta = -2.1 \pm 0.1$, and $E_p = 54.6 \pm 20.9$ keV, which are consistent with those derived by the previous works [6, 7]. This spectral property is similar to one of the recently identified class of the X-ray flash (XRF) [8, 10]. The observed fluence of the entire emission is $S(20\text{--}2000 \text{ keV}) = (4.0 \pm 0.74) \times 10^{-6} \text{ erg cm}^{-2}$, thus we find $E_{iso} = (6.4 \pm 1.2) \times 10^{47} \text{ ergs}$. The fluence ratio is $R_s = S(20\text{--}50 \text{ keV})/S(50\text{--}320 \text{ keV}) = 0.34 \pm 0.036$.

MODEL OF PROMPT EMISSION OF GRB 980425

We use a simple jet model of prompt emission of GRBs, where an instantaneous emission of infinitesimally thin shell is adopted [9, 21, 22, 23, 24]. See Yamazaki et al. [24] for details. We fix model parameters as $\alpha_B = -1$, $\beta_B = -2.1$, $\gamma v'_0 = 2600 \text{ keV}$, and $\gamma = 100$. Normalization of emitted luminosity is determined so that E_γ be observationally preferred value of $1.15 \times 10^{51 \pm 0.35} (h/0.7)^{-2} \text{ ergs}$ [3] when we see the jet from the on-axis viewing angle $\theta_v = 0$. Our calculations show that on-axis intrinsic peak energy becomes $E_p^{(\theta_v=0)}(1+z) \sim 1.54\gamma v'_0 \sim 4.0 \text{ MeV}$, in order to reproduce the observed quantities of GRB 980425. Indeed, there are some GRBs with higher intrinsic E_p ; for example, $E_p(1+z) \sim 2.0 \text{ MeV}$ for GRB 990123 and 3.6 MeV for GRB 021004 [1, 2].

The left panel of Figure. 1 shows E_{iso} as a function of the viewing angle θ_v . When $\theta_v \leq \Delta\theta$, E_{iso} is constant, while for $\theta_v \geq \Delta\theta$, E_{iso} is considerably smaller than the typical value of $\sim 10^{51-53} \text{ ergs}$ because of the relativistic beaming effect.

We next calculated E_p and R_s for the set of $\Delta\theta$ and θ_v^* that reproduces the observed E_{iso} of GRB 980425. For our parameters, $\Delta\theta$ should be between $\sim 18^\circ$ and $\sim 31^\circ$, and then θ_v^* ranges between $\sim 24^\circ$ and $\sim 35^\circ$ in order to reproduce the observation results. Thorough discussions on the right panel of Figure 1 is found in [24].

DISCUSSION

We have found that when the jet of opening half-angle of $\Delta\theta \sim 10\text{--}30^\circ$ is seen from the off-axis viewing angle of $\theta_v \sim \Delta\theta + 6^\circ$, observed quantities can be well explained. Observed low variability can be explained since only subjects at the edge of the cone contribute to the observed quantities [21]. If the time unit parameter $r_0/c\beta\gamma^2$ is about 3 sec, which is in the reasonable parameter range, the spectral-lag of GRB 980425 can be also explained.

Our result might be able to explain the slowly decaying X-ray afterglow of GRB 980425. If we assume the density profile of ambient matter as $n = n_0(r/r_{ext})^{-2}$ with $n_0 r_{ext}^2 = 4 \times 10^{17} \text{ cm}^{-2}$, the break in the afterglow light curve should occur at $t_b = 3.1 \times 10^2 \text{ days } E_{51}(\Theta/0.4 \text{ rad})^2$, where Θ is defined by $\Theta^2 = (\Delta\theta)^2 + \theta_v^2$, and E is the total energy in the collimated jet [12, 13]. Since our calculation suggests Θ should range between 0.4 and 0.67 rad, t_b is consistent with the observation [13]. Up to the break time, one can estimate the flux in the X-ray band as $F(2\text{--}10 \text{ keV}) \propto t^{-0.2}$, where we assume $\theta_v \gg \Delta\theta$ and the spectral index of accelerated electrons as $p = 2.2$ [12, 13]. This result is also consistent with the observation [15, 16]. Furthermore,

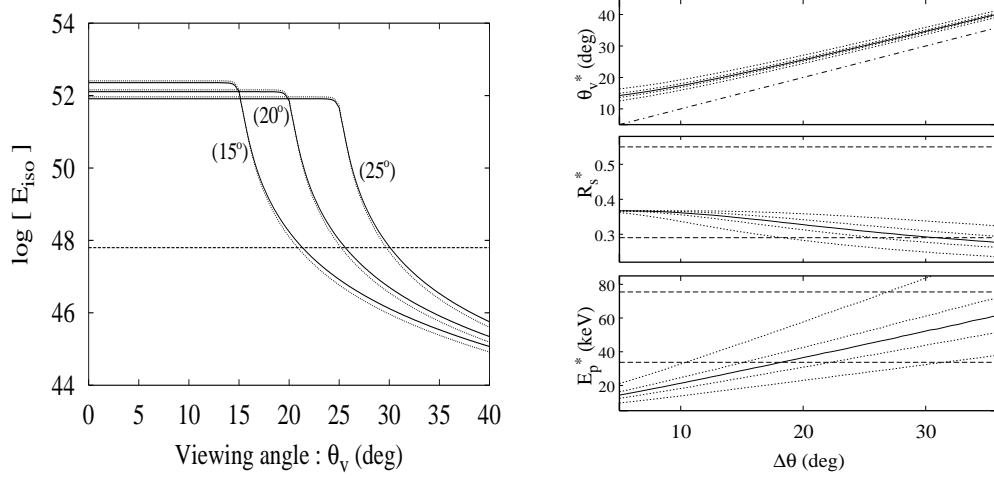


FIGURE 1. (Left panel): the isotropic equivalent γ -ray energy E_{iso} is shown as a function of the viewing angle θ_v for a fixed jet opening half-angle $\Delta\theta$. The source is located at $z = 0.0085$. The values of $\Delta\theta$ are shown in parentheses. Solid lines correspond to the case of $\gamma v'_0 = 2600$ keV, while dotted lines $\gamma v'_0 = 1300$ keV. Horizontal dashed line represents the observed value of GRB 980425. (Right panel): the upper panel shows θ_v^* for which E_{iso} is the observed value of GRB 980425, while the middle and the lower panels represent the fluence ratio $R_s^* = R_s^{(\theta_v=\theta_v^*)}$ and the peak energy $E_p^* = E_p^{(\theta_v=\theta_v^*)}$, respectively. Solid lines correspond to the fiducial case. The dotted lines represent regions where E_{iso} becomes $(6.4 \pm 1.2) \times 10^{47}$ ergs when E_γ is in 1σ and 5σ level around the fiducial value, respectively. The dot-dashed line in the upper panel represents $\theta_v^* = \Delta\theta$. Horizontal dashed lines in the middle and the lower panels represent the observational bounds.

the adopted value of $n_0 r_{ext}^2$ corresponds to the mass loss rate of the progenitor star $\dot{M} = 1.3 \times 10^{-6} M_\odot \text{ yr}^{-1}$ ($v_W/10^3 \text{ km s}^{-1}$), which might be able to explain the radio data (see [20]).

The observed quantities of small E_p and large fluence ratio R_s are the typical values of the XRF [6, 8, 10]. The operational definition of the *BeppoSAX*-XRF is a fast X-ray transient with duration less than $\sim 10^3$ s which is detected by WFCs and not detected by the GRBM. If the distance to the source of GRB 980425 were larger than ~ 90 Mpc, the observed flux in the γ -ray band would have been less than the limiting sensitivity of GRBM, so that the event would have been detected as an XRF.

We might be able to explain the origin of a class with low E_γ such as GRB 980326 and GRB 981226 [3], and GRB 030329 whose E_γ is about $\sim 5 \times 10^{49}$ ergs if the jet break time of ~ 0.48 days is assumed [18, 19]. Let us consider the jet seen from a viewing angle $\theta_v \sim \Delta\theta + \gamma_i^{-1}$, where γ_i is the Lorentz factor of a prompt γ -ray emitting shell. Due to the relativistic beaming effect, observed E_γ of such a jet becomes an order of magnitude smaller than the standard energy. At the same time, the observed peak energy E_p is small because of the relativistic Doppler effect. In fact, the observed E_p of the above three bursts are less than ~ 70 keV. In our model the fraction of low- E_γ GRBs becomes $2/(\gamma_i \Delta\theta) \sim 0.1$ since the mean value of $\Delta\theta \sim 0.2$, while a few of them are observed in ~ 30 samples [3]. In later phase, the Lorentz factor of afterglow emitting shock γ_f is smaller than γ_i , so that $\theta_v < \Delta\theta + \gamma_f^{-1}$. Then, the observed properties of afterglow may

be similar to the on-axis case $\theta_v \ll \Delta\theta$; hence the observational estimation of the jet break time and the jet opening angle remains the same.

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